Final Progress Report for Improved Upper Ocean/Sea Ice Modeling in the GISS GCM for
Investigating Climate Change (Martinson, Rind and Parkinson)

This project built on our previous results in which we highlighted the importance of sea ice in overall climate sensitivity by determining that for both warming and cooling climates, when sea ice was not allowed to change, climate sensitivity was reduced by 35-40% (Rind et al., 1995). We also modified the GISS 8°x10° atmospheric GCM to include an upper-ocean/sea-ice model involving the Semtner three-layer ice/snow thermodynamic model (Semtner, 1976), the Price et al. (1986) ocean mixed layer model and a general upper ocean vertical advection/diffusion scheme for maintaining and fluxing properties across the pycnocline. This effort, in addition to improving the sea ice representation in the AGCM, revealed a number of sensitive components of the sea ice/ocean system. For example, the ability to flux heat through the ice/snow properly is critical in order to resolve the surface temperature properly, since small errors in this lead to unrestrained climate drift.

The present project, summarized in this report, had as its objectives: (1) introducing a series of sea ice and ocean improvements aimed at overcoming remaining weaknesses in the GCM sea ice/ocean representation, and (2) performing a series of sensitivity experiments designed to evaluate the climate sensitivity of the revised model to both Antarctic and Arctic sea ice, determine the sensitivity of the climate response to initial ice distribution, and investigate the transient response to doubling CO2.

Model improvements.

The model improvements involved improving the thermodynamics of the sea ice, making them more appropriate for thicker perennial ice fields, adding ice dynamics, improving the ocean lateral flux representation, and several additional items (e.g., improving the representation of freshwater input from runoff and iceberg discharge), listed below. While all of these are useful for improving the Antarctic sea ice representation, they are even more important for the Arctic, in view of the thicker ice, considerable internal ice stress, and more complicated ocean circulation.

Most of these model improvements have now been completed. Specifically, for the improved ocean treatment, we have adopted the GISS three-dimensional dynamical ocean model of Russell et al. (1995). This is consistent with initial recommendations not to pursue intermediate-level ocean models of uncertain characteristics and quality. Working with Russell, we have modified the model to represent reasonable mixed layer physics (shown to be important in our previous work), and added multi-level sea ice thermodynamics (the number of additional ice/snow layers is a simple parameter setting). The latter modification reflects our previous findings that showed a sensitivity of the surface ice/snow temperature, and thus model climate, on the conduction of heat through the ice and snow. We now have multiple ice/snow layers to treat this more accurately. We have found that four layers is adequate, though we have not rigorously investigated this sensitivity yet. The mixed layer physics have been tested against a one-dimensional ocean-ice model that was used to test the original AGCM modifications. The tests, which suggest that the modified ocean model properly represents the mixed layer physics critical in the ocean-ice interaction, also addressed the influence of vertical resolution in the upper ocean on the sea ice evolution (experimenting from 13 to 40 layers). To our surprise, the results were fairly robust to the coarser resolution. Consistent with this, the inclusion of the Large (1996) mixed layer scheme, designed to better represent key mixed layer physics while accommodating the coarser vertical resolution of GCMs, did not seem to introduce any significant changes to the dynamic ocean model. However, further to our surprise, when the dynamic model is run coupled to the atmospheric GCM we reached the opposite conclusion: the inclusion of the KPP scheme made a significant difference. In particular, for the

first time, the model's thermohaline circulation is now considerably more consistent with observations.

Several studies have shown the sensitivity of the ice field simulations and climate response to the dynamical treatment of the ice. Consequently, we opted to work with three different dynamical models in an effort to evaluate their influence in the experiments we have been conducting with the GCM. Originally, the simplest, empirical treatment, in which the ice moves at a set fraction of the wind speed and at a specified angle relative to the wind, consistent with the simple relationship found by Martinson and Wamser (1990) and Wamser and Martinson (1993) for the Antarctic was implemented. The Flato and Hibler (1992) cavitating fluid model has been coded, successfully tested, and is running in the dynamical ocean model. We are incorporating an even more detailed model, that of Tremblay and Mysak (1997) (Tremblay is a post-doc at Lamont involved in this project), to complete the dynamical model development, but this coupling is still not completed as several particular coupling issues must first be resolved (they are currently being addressed). The most time consuming change involves a transformation of the ice model's numerical grid system to the grid used by the GISS model. Recent findings from Geiger and Hibler (1997) showed that even the most simplistic ice treatment can produce fairly reliable ice speeds, but only the more detailed treatments can produce consistent divergence and curl fields, which are also critical to driving the ocean circulation and associated fluxes. Therefore, the justification of using the more simple models may no longer be tenable, but since we have them functioning, we still plan to assess the net impact of the different treatments at these larger scales for the current generation of climate models. At present, our results show that the Flato-Hibler model does produce better results in the Arctic over the case where the ice drifted proportional to the winds (as we had originally suggested).

Other changes to the ocean model include modifying the ocean convection scheme, which resulted in significantly improved NADW production and simulation (which, as reported above, was then further improved upon inclusion of the KPP mixed layer scheme); reducing the magnitude of the filter designed to preserve numerical stability (Shapiro filter); adding fresh water runoff in regions of iceberg discharge, using the IPCC (1996) estimate of iceberg impact (which is about 1/3 lower than what the GISS coupled model requires to achieve zero mass balance over Antarctica); and including a more precise depiction of the "blocking factors" that affect sea ice advection through narrow passages around the Arctic Ocean.

The ocean dynamic model can now be run fully coupled to the GISS AGCM (without flux corrections). Control runs using this coupled GISS coupled GCM, when including the modifications described above, provide a reasonable sea ice distribution (though obviously not perfect) in both hemispheres. Also, the new model appears capable of maintaining the NADW circulation much more accurately than that shown in Russell et al. (1995) and in the IPCC (1996), using the unmodified model, at least on the 40 year time span when several of these changes are combined. Many of the sensitivity experiments associated with these model improvements and their influence are being written up in the Ph.D. thesis of Suki Seth, a GISS graduate student with whom we have been working (and advising) on this work.

Sensitivity experiments.

The sensitivity experiments conducted to date, using the modified AGCM, include the following: (1) we have tested the doubled atmospheric CO_2 sensitivity to initial ice characteristics and distributions, (2) we have rerun our experiments for doubled CO_2 using the revised upper ocean model representation and simplest ice dynamics on a finer resolution model than initially run; and (3) we have generated the control run for the transient response to increasing atmospheric CO_2 using the coupled GCM (without the improvements discussed above). The results from the first experiment have been published in Rind et al. (1997). Using "q-fluxes" (specified spatially/temporally-varying ocean heat fluxes), these established that in the GISS AGCM,

hemispheric differences reflecting sensitivities to different sea ice properties became evident: in the Southern Hemisphere, the sea ice extent in the control run was most important for the subsequent doubled CO2 climate sensitivity, while in the Northern Hemisphere, the most important property was sea ice thickness. In both cases, increased sensitivity resulted when more sea ice was removed. In the Southern Hemisphere, the predominant first-year sea ice is always sufficiently thin so that how much ice is removed depends upon the initial extent of sea ice coverage. In the Northern Hemisphere, the multiyear sea ice, being thicker, requires more energy for complete melting, and therefore its thickness is the more important characteristic.

Also important for climate sensitivity is where the sea ice is removed. A direct effect of sea ice on the net global radiation balance depends upon its influence on the planetary albedo, so sea ice changes at latitudes which receive more sunshine in the appropriate season are more important. In the GISS model simulations, sea ice in the Southern Hemisphere was more important for climate sensitivity; climate sensitivity increased by about 0.02°C per percent Southern Hemisphere sea ice removed. Hence examination of the likelihood of sea ice change in the Southern Ocean is of primary importance for this issue.

The second set of experiments reveals a potentially important role that the ocean-ice interaction may play, at least in the Southern Hemisphere and northern Nordic Seas, where the marginal stability of the water column allows strong interaction. In these experiments, because of the marginal stability of the water column, the growth of ice drives mixed layer entrainment, through salt rejection, that introduces warmer thermocline water into the surface layer, contributing toward melting or at least inhibition of further ice growth. Thus, the warm ocean deep water represents a source of heat that provides a negative feedback — that is, heat loss promotes ice growth, which drives an ocean entrainment heat flux that inhibits further ice growth. Conversely, ice melt enhances the water column stability reducing the effectiveness of this negative feedback.

When these processes are properly represented in the GISS AGCM, the doubled CO2 response is considerably different than the response obtained when the ocean-ice interaction was simply specified through the q-flux. In the latter case, the Antarctic sea ice fields were reduced by more than 50% in winter, directly reflecting a warmer atmosphere, and thus milder winters with weaker air-sea fluxes. However, when the ice-ocean interaction is introduced, in the GISS coarse-resolution model, the changes in the atmosphere are offset by changes in the ocean vertical structure, which reduces the ocean heat flux, compensating for the weaker atmospheric fluxes. Consequently, the air-sea heat fluxes are adjusted with very little change in the sea ice distribution (at least for several decades following the quasi-equilibrium response; possibly slower feedbacks may eventually lead to a more dramatic response). As reported for the previous results, 35-40% of the global warming response was attributed to the changes in the sea ice fields, of which 70% of these changes occurred in the Antarctic. With the ocean-ice interaction eliminating these Antarctic sea ice field changes, the global warming was reduced by 30% of that realized when the ocean-ice interaction was not included (a global warming of 3.3° C instead of 4.7° C). However, when this same experiment is run in the finer resolution GISS AGCM (which had to be modified to allow for double precision, unlike the case for the coarse model), we find that the global warming is comparable, but the change in the sea ice fields dramatically different. This is a disturbing result, but as we pointed out in this proposal, such inconsistencies must be identified and understood. Since finding these conflicting results (arising from the model resolution and/or higher order numerical precision) we have spent considerable time and effort running additional experiments and defining and examining new diagnostics to understand the source of the conflict. At present, we are still investigating this (we have designed and examined dozens of experiments to date on this).

The transient experiment for increasing CO2, using the unmodified coupled GCM, establishes the baseline against which the improvements to the upper ocean and sea ice can be gauged. Results from this run show a concentration of the response in the high latitude regions, mainly reflecting

changes in deep water formation/ventilation, which in turn alters the poleward heat flux and regional heat convergence. The transient experiment has been completed, but we are still performing multiple model experiments with new diagnostics to better understand the nature of the response (we get some mid-latitude changes in precipitation and temperature, and we are trying to determine the cause and effect, as well as underlying mechanism for the changes).

The model modifications completed (or nearly completed) in the efforts described here, have provided us with several capabilities. First, they are sufficient to capture critical aspects of the important ocean-ice interaction. This is crucial in the Southern Hemisphere and in the Nordic Seas of the Arctic where deep and bottom water formation (e.g., NADW) occurs and the ocean is marginally stable. The introduction of detailed ice dynamics, improved ice thermodynamics, and an active ocean model allows us to address additional issues regarding the Arctic sea ice fields as well, and we have begun addressing Arctic issues as a consequence. Certainly, there are many additional details, e.g., the ice-cloud feedback, the influence of spatial heterogeneity in ice characteristics, and the complexities of the surface energy balance, that must be ultimately addressed. But, we have succeeded in introducing those influences that we had targeted for inclusion in this project.